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The past four years have again seen significant advances in geoid computations. In fact, the number of references has more than doubled over the last report. One of the most exciting new developments of this period has been the production and dissemination of digital data sets through CD-ROM media and the INTERNET network. For this reason, a section devoted to "electronic publication" of digital resources can be found at the end of this report.

NATIONAL GEOID COMPUTATION

During this period, a new high-resolution geoid model, GEOID93, was released by the National Geodetic Survey (NGS) (Milbert and Schultz, 1993a). This model incorporated new terrain corrections, improved quality gravity data (courtesy of DMA), the second order term of the normal gravity gradient, and the OSU91A model. Also, for the first time, a 3' x 6' high-resolution geoid was computed for the state of Alaska. Two deflection of the vertical models, DEFLEC90 (Milbert 1994d), and DEFLEC93 (Milbert and Schultz, 1993b) were also computed and released by NGS in this period. These models use cubic splines of geoid profiles to develop deflections at the geoid. The deflections are then upward continued by the normal curvature of the plumbline correction. However, with the new deflection model for Alaska, the actual curvature of the plumbline is modeled by a variant of Eq (5.32) pg. 195 of Heiskanen and Moritz.

A NEW GLOBAL GEOPOTENTIAL MODEL UNDER CONSTRUCTION

R. H. Rapp and R. S. Nerem (1995) report on a joint Goddard Space Flight Center/Defense Mapping Agency (GSFC/DMA) project to compute an improved 360 degree spherical harmonic model of the Earth's geopotential. This model will incorporate the latest satellite tracking data, as well as altimeter data from TOPEX/Poseidon, ERS-1, and the Geosat Geodetic Mission. The model will also incorporate new surface and ship gravity data covering the globe, including the former Soviet Union. NGS will participate in the International Geoid Service Special Working Group on the GSFC/DMA Model Evaluation, and will use the final GSFC/DMA model as a basis for a new, high-resolution, GEOID96 geoid height model. The GSFC research team is lead by R. S. Nerem, and the project manager for DMA is Larry Kunz.

A BOOK DEVOTED TO THE GEOID

The book, "Geoid and Its Geophysical Interpretations", edited by P. Vanicek and N. T. Christou was published in 1994. U. S. contributors were R. H. Rapp, global geoid determination; V. Zlotnicki, the geoid from satellite altimetry; R. Sailor, signal processing techniques; C. Bowin, the geoid and deep earth mass anomaly structure; B. F. Chao, the geoid and Earth rotation; and R. S. Nerem and C. J. Koblinsky, the geoid and ocean circulation. When one considers the reputations and accomplishments of these individuals and the other contributing authors, it is seen that the release of this book stands as a significant event.

GLOBAL GEOPOTENTIAL MODELS

In this period, several new geopotential models were computed, of both low and high degree. In addition, significant work was done in accuracy analysis of these models. For a perspective on the progress in this field, Vetter (1994) provides a history from the earliest geopotential models to our current status.

In the area of techniques, Lerch (1991) reports on a data weighting method, utilizing data subset adjustments, to compute geopotential models with heterogenous, satellite-only data sets.

In the area of accuracy analysis, we can begin with an assessment of GEM-T1. Lerch, Patel, and Klosko (1991) compare the GEM-T1 (satellite tracking data only) geopotential model with 5 anomalies derived from satellite altimetry. Bertiger, Wu, and Wu (1992) performed a covariance analysis to predict the expected improvement to GEM-T2 from 10 days of GPS-controlled TOPEX/Poseidon (T/P) data. Wu and Yunck (1992) also used this 10 day scenario with an emphasis on T/P orbits. Wagner and Klokocnik (1994) use Geosat and ERS 1 crossovers to assess the accuracy of the GEM-T2 model. By use of latitude lumped coefficients, Klokocnik and Wagner (1994) test the GEM-T2 error estimates with Geosat ERM crossovers.

Global geopotential models, GEM-T3, and GEM-T3S, complete to n=50, were computed by Lerch, *et al*. (1992) using satellite tracking, altimeter, and surface gravity observations. Additional description of GEM-T3 is provided by Lerch, *et al*. (1994). In a later study, Nerem, *et al*. (1994a) analyze DORIS tracking of SPOT 2 to develop a modification to GEM-T3, and then they compare this result to other geopotential models. Rapp and Wang (1993) compare the geopotential models OSU91A, GEM-T3, and GRIM4-C2 with Doppler and GPS derived heights on vertical benchmarks.

In support of the TOPEX/Poseidon (T/P) project, Nerem, *et al*. (1994c) computed the JGM-1 (pre-launch) and the JGM-2 (post-launch) models, complete to n=70. Estimates indicate T/P radial orbit error at 2 cm, and geoid commission error at 25 cm for wavelengths greater than 2500 km. While a JGM-3 model has been computed, it has not yet been officially documented.

In the area of high-degree global geopotential models, Rapp, Wang and Pavlis (1991) computed the OSU91A model, complete to n=360. It should be noted that this computation included development of a sea surface topography model.

THE MARINE GEOID, SATELLITE ALTIMETRY AND SEA SURFACE TOPOGRAPHY

During this period, the launch of new satellite altimetry missions and the release of subsets of the Geosat Geodetic Mission (GM), have been instrumental in major progress on the marine geoid and the synergistic improvement of Sea Surface Topography (SST) models. Beginning first with mean sea surfaces, Marsh *et al*. (1992) reports on MSS-9012, a global mean sea surface obtained from GEOS-3 and Seasat altimeter data. Wang and Rapp (1992) computed a mean sea surface from a year of the Geosat ERM mission and also developed some ocean variability results. In subsequent work, Rapp, Yi, and Wang (1994) computed a sea surface from cycles 4-54 of TOPEX, solved for differences with respect to the 1992 OSU surface, and got geoid gradient agreement at 0.9cm/km. Bhaskaran and Rosborough (1993) perform a simulation, and demonstrate that an improved model for altimeter orbit error covariance improves the recovered regional mean sea surface. Wang and Rapp (1991) report on the impact of cross-track geoid gradients on track-averaged altimetry.

The new satellite altimetry missions, coupled with declassification of subsets of the Geosat Geodetic Mission (GM), have also given new insights into the marine gravity field. McAdoo and Marks (1992a and 1992b) and Sandwell (1992) compute and analyze the gravity fields of the Southern ocean from declassified GM Geosat data (south of 60S). In a later release, the GM data was declassified south of of 30S. Marks, McAdoo, and Smith (1993) computed this marine gravity field and reported on the Southwest Indian Ridge. A preliminary study by McAdoo and Marks (1992c) found that ERS-1 altimetry could achieve 30 km along-track resolution, but that a 35 day repeat hampered cross-track resolution. The ERS-1 data were used by Laxon and McAdoo (1994) to compute the Arctic marine gravity field up to 82N; which was then compared with shipborne data. Basic and

Rapp (1992) predict gravity anomalies at 1/8 spacing by means of collocation using GEOS-3, Seasat, and Geosat altimeter data augmented by ETOPO5U bathymetry.

Geoid models in marine areas have proven to be highly effective in the measurement of Sea Surface (dynamic) Topography (SST). For example, Nerem, *et al*. (1994b) computes an SST field, complete to n=15 by subtracting GEM-T3 geoid height from satellite altimetry. In this case, they were able to see the El Nino. In a different procedure, Porter, Dobson, and Glenn (1992) compute a "synthetic geoid" by subtracting SST obtained from a fluid dynamics model, from Geosat altimetry.

In studies involving the Gulf Stream, Rapp and Wang (1994) computed a 3' x 3' geoid grid using land, ship, and bathymetrically-inferred gravity, which was then used with Geosat altimetry to estimate SST. In a follow-on, Rapp and Smith (1994) used a gravimetric geoid and TOPEX/Poseidon altimetry to compute SST. A Gulf Stream velocity model was then fit to the results and compared with NOAA AVHRR data.

Martel and Wunsch (1993) did a combined inversion of hydrography, current meter data, and altimetric elevations to compute North Atlantic circulation. In this approach, their aim was an improvement of both geoid and oceanographic features.

THEORY, TECHNIQUES, AND RESULTS

Again, significant progress was seen during this period. Rapp (1992) discusses the sensitivity of global geoid models to issues such as the Earth's GM, semimajor axis (a), and local vertical datums. I find this paper particularly noteworthy, since Rapp points out that one obtains a height anomaly, not a geoid height, under the standard evaluation of geopotential coefficients. The implications are far reaching, since we must now consider the *kind* of gravity anomaly, and the *kind* of "geoid" that we want to obtain from a set of coefficients. Clearly, digital terrain and density data sets, and/or related data, such as Bouguer anomalies, will play a role here. I'm sure there will be additional research presented on this topic in the future.

Even more fundamentally, questions on the definition of the geoid have been raised by Rapp (1994c). In this paper, Rapp reviews the geodetic and the oceanographic definitions of the geoid, and discusses the difficulties of realizing a geoid under these different definitions. Also of note, Heck (1991) examines the vectorial and scalar free Boundary Value Problems (BVP) and the fixed gravimetric BVP. He finds that through explicit formulation, decimeter differences can be found.

Wang (1993) describes an FFT formulation for the minimum error combination of geopotential coefficient and terrestrial gravity data. Hwang (1993b) developed an FFT method to form normals for a spherical harmonic analysis when one is given incomplete data coverage. And, Bettadpur, Schutz, and Lundberg (1992) report on data storage and CPU execution times for spherical harmonic synthesis and least squares accumulation on vectorizing supercomputers for a simulated, one month, gradiometer mission.

By means of a Gram-Schmidt orthonormalization procedure, Hwang (1991) developed a compact representation of Sea Surface Topography (SST), and found that the formulation provided better separation of SST and geoid signals in altimetry. Using the same procedure, Hwang (1993a) reports that 99.9% of the Levitus SST model can be represented in an n=24 orthonormal model.

Jekeli (1991) examines statistical tests for a Gaussian stochastic process when given a residual gravity field in a local, planar, region. Milbert (1991e) points out the issue of vertical datum errors when combining GPS, leveling, and geoid models, and shows an adjustment approach to accommodate these errors. Lee and Mezera (1992) study interpolation of 18 GPS benchmarks in a 25 sq. mile area with a cubic Hermite polynomial. While a 2 cm result was obtained, no gravity data were used, and no analysis of GPS height error was performed. Milbert (1991a) presents a family of covariance functions based on degree variance models that are efficiently evaluated by elliptic integrals.

Geoid models in local areas also received significant attention during this period. In a computation of the local geoid on the island of Maui, Smith (1992) found significant improvements when using 3" x 3" digital terrain for terrain corrections. The application of the integrated geodesy formulation in a rugged, high-altitude setting by Milbert and Dewhurst (1992) showed a requirement to use isostatic anomalies, and a need to develop an empirical cross-covariance function between gravity anomalies and anomalous geopotential. Weigel (1993) studied geoid heights obtained from variable sized caps using Meissl's modification to Stokes' method. In this work, he identified error due to vertical datum inconsistencies. Potterfield (1994) used a least-squares procedure and a Jordan 3rd-order Markov process model to relate GPS on benchmarks to high resolution geoid grids. Boener (1994) computed a high resolution, local geoid for Monterey Bay with software obtained from the National Geodetic Survey. He estimates the accuracy at 3.5 cm at a 5 km distance, and he compared the results with ship-borne GPS to derive sea surface topography. Geoid models in three regions, North Dakota, Nevada, and, Ecuador were computed by Balde (1995) and were then used with GPS to establish orthometric heights for gravity surveys. A report on the techniques used to compute GEOID90 can be found in Milbert (1991f and 1991c). An accuracy assessment of GEOID90 for the Commonwealth of Virginia is presented in Milbert (1991b).

During a year of study at the National Geodetic Survey, Yuki Kuroishi computed several 3' x 3' models of the geoid for the nation of Japan. The adopted JGEOID93 model was found to have 8.6 cm error in a 400x600 km area, when comparing GPS/leveling data sets. This figure is comparable to the error levels seen in the United States for the GEOID93 model in similar sized areas. One reference to this work is Kuroishi, Milbert, and Schultz (1993)

As reported at various meetings of the American Geophysical Union, GEOID93 geoid model comparisons with over 1400 GPS/leveling points now show 23.7 cm RMS. The error is long wavelength, with a decaying exponential-type empirical covariance function model of L=450 km. When the geoid model is augmented by a long-wavelength correction computed with collocation, the residual error is 6.2 cm RMS. This error is mostly white, with a correlated part of 2.6 cm. This shows remarkable short wavelength fidelity of national models on 3' grids.

GEODETIC AND GEOPHYSICAL APPLICATIONS

In geodetic applications, Satalich (1994) used GPS leveling in a 55 km corridor on the Santa Clara River. After a trend removal, GEOID93 showed a 1.1 cm RMS agreement. Parks and Milbert (1994) studied the effect of additional gravity in the mountainous San Diego County region of the United States. Of particular note, they found a geoid error/gravity error ratio of 3 to 4 mm/milligal. Though a GEOID93 model for Alaska, Cohen, *et al*. (1995) were able to relate 1964 leveling to 1993 GPS heights to detect post-seismic uplift of the Kenai Peninsula.

Wessel (1993) analyzed both the topography/bathymetry and the geoid of the Hawaii-Emperor seamount chain. He found indications of possible reheating and hotspot penetration. King and Hager (1994) developed the geoid signature of a subducting slab with temperature dependent viscosity. Their results show a requirement for higher resolution geoid models over subduction zones. And, Mitrovica and Peltier (1993) developed a new formulation for secular variation in the gravitation of a spherically symmetric, self-gravitating, viscoelastic planet when subjected to an arbitrary surface load consistent with ocean loading.

VERTICAL DATUMS

In this period, research on the definition and relationships of vertical datums has received renewed interest, with emphasis on the geoid and long geopotential connections. Pavis (1991) performed an error analysis involving gravity data in caps combined with satellite to satellite tracking, to compute long geodetic connections for vertical datum relationships.

After considerable study of the topic, Rapp and Balasubramania (1992) report on a conceptual formulation for a world height system. In this report, they relate vertical datums by precise space positioning, geopotential models, and surface gravity in a 2 cap. Their work indicates that one can establish a regional datum to 3 kGal cm and can compute geopotential differences (connections) to 4 to 20 kgal cm.

Balasubramania (1994) continued this method of relating vertical datums. He used modified Stokes and least-squares collocation to combine surface gravity in a cap with OSU91A values. He then obtained local accuracy to 5 cm and connections at a 5 to 23 cm accuracy. In a simplified approach, Rapp (1995) used a variant of OSU91A (n=360), where JGM-2 coefficients were substituted for OSU91A for n=2,70, in conjunction with Doppler data to compare various national vertical datums, including NGVD29 and NAVD88. A review of the concepts and status of vertical datum relationships was presented by Rapp (1994b). An argument to use the geoid as a bathymetry reference is made by Kumar (1994). Zilkoski, Richards, and Young (1992) found an inconsistency between local mean sea level heights (1960-78) and both NAVD 88 and orthometric heights computed from VLBI and GEOID90 (Milbert 1991f).

DIGITAL RESOURCES

As discussed at the beginning of this report, this period has seen massive dissemination of digital data sets through CD-ROM media and the INTERNET network. The sheer size of these data sets, their comprehensiveness, and ease of access mandate that they be documented in some fashion. In this section I focus on those data sets most likely to be of interest to those involved in geoid research. Certainly, not all data sets are available for on-line access. But, one can often find subsets or products derived from base data sets. Due to the dynamic character of electronic publication, it is impossible to provide an exhaustive listing. For this reason, World Wide Web (WWW) "home pages" are provided. Users are strongly encouraged users to browse "down" any pertinent paths, as well as browse "along" any other links they may encounter.

Home pages

http://www.ngs.noaa.gov (GEOID93 and DEFLEC93)

http://www.grdl.noaa.gov

http://www.ngdc.noaa.gov

http://www.nodc.noaa.gov

http://www.jpl.nasa.gov

http://www.usgs.gov

http://info.er.usgs.gov

http://helmert.mps.ohio-state.edu (Department of Geodetic Science and Surveying, OSU)

Pointers to various data sets of interest

http://sun1.cr.usgs.gov/glis/hyper/guide/1_dgr_demfig/index1m.html -- index 3" elevations http://fermi.jhuapl.edu/states/states.html -- relief maps of states

http://www.ngdc.noaa.gov:80/seg/potfld/grav.html -- images of gravity

http://www.nodc.noaa.gov/NODC-cdrom.html -- index Geosat CD

http://podaac-www.jpl.nasa.gov/TopexPoseidon_Products.html -- index TOPEX CD

Anonymous FTP access

ftp.ngs.noaa.gov

ftp.ngdc.noaa.gov

edcftp.cr.usgs.gov:/pub/data/DEM/250 -- 3" gridded digital terrain data

ftp.jpl.nasa.gov:/pub/topex -- images of TOPEX/Poseidon data sets

The National Geophysical Data Center (NGDC) of NOAA distributes the following CD-ROM's that could be used in geoid computation:

Gravity (1994) -- gravity point data, networks, gravity anomaly grids, geoid, and boundary data.

TerrainBase -- improved 5-minute, global, digital terrain data

Global Relief -- topography and bathymetry, coastlines, ocean gravity anomalies.

Geophysics of North America -- magnetics, gravity, seismology, and topography complied by the Geological Society of America.

GEODAS (and Update) -- marine geophysical trackline data including bathymetry, magnetics, gravity, and seismic.

The National Oceanographic Data Center (NODC) of NOAA distributes the following sets of CD-ROM:

Geosat Altimeter Crossover Differences from the Geodetic Mission

Geosat Geophysical Data Records (GDR) from the Geodetic Mission for 30S to 72S

Geosat Altimeter Data, Improved (T2 GDR) from the Exact Repeat Mission

The Jet Propulsion Lab (JPL) of NASA distributes the following sets of CD-ROM:

Product # 28 --TOPEX/Poseidon merged geophysical data record

Product # 35 --TOPEX altimeter sensor data record

Product # 36 --TOPEX altimeter geophysical data record

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